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(54) **DC RESPONSIVE TRANSDUCER WITH ON-BOARD USER ACTUATED AUTO-ZERO**

(75) Inventors: **Thomas F. Connolly**, Lake Forest, CA (US); **Ming Zhong**, Guangdong (CN)

(73) Assignee: **Measurement Specialties, Inc.**, Hampton, VA (US)

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***G01P 15/00*** (2006.01)

(52) **U.S. Cl.**
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USPC .............. 324/160, 162, 207.12, 225; 73/1.37, 73/1.38, 1.85, 1.88, 514.33, 98, 649, 754, 73/765, 766; 340/514, 540; 374/1, 374/170–172, 183; 702/98
See application file for complete search history.

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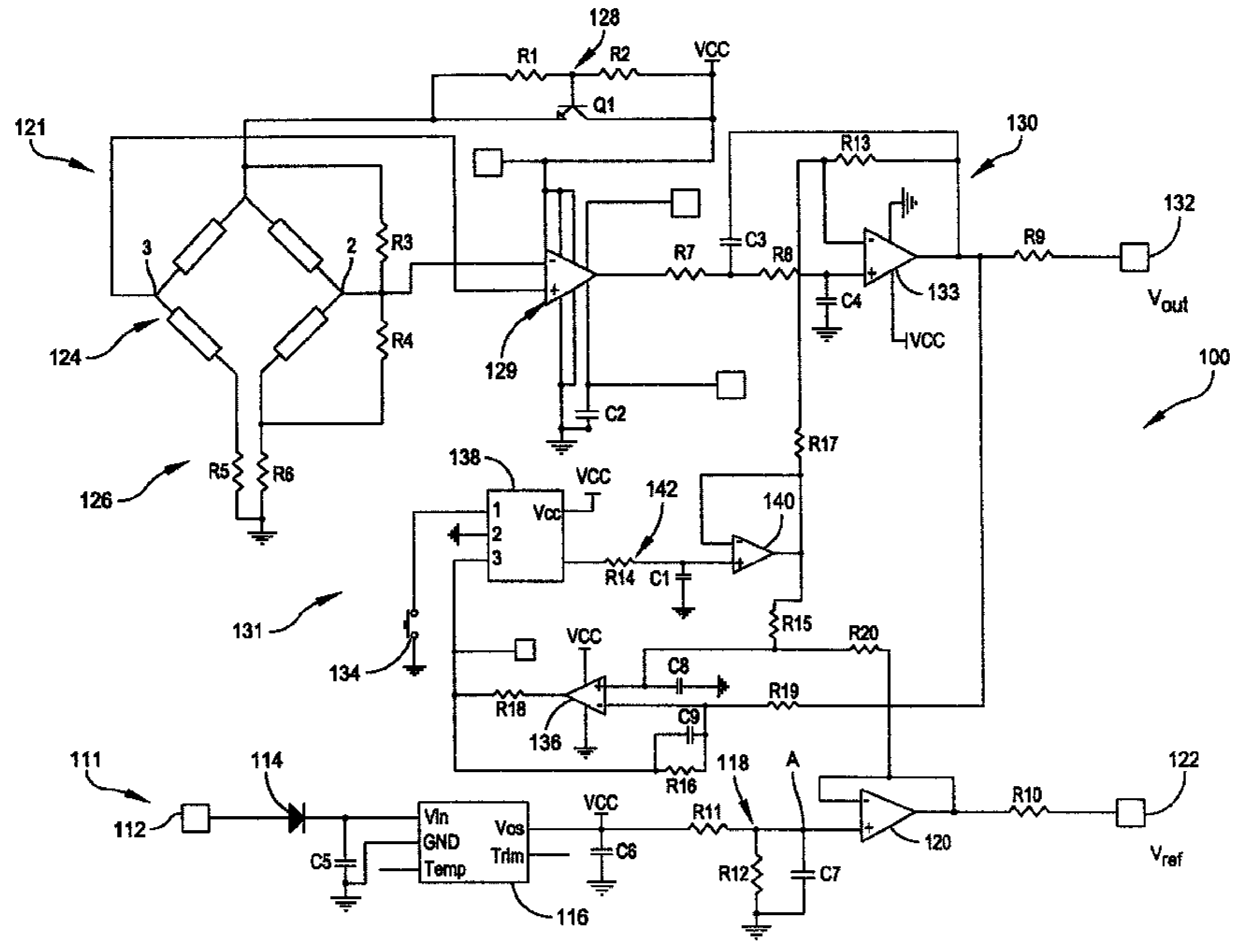
*Primary Examiner* — Arleen M Vazquez
*Assistant Examiner* — Hoang X Nguyen
(74) *Attorney, Agent, or Firm* — Howard IP Law Group, PC

(57) **ABSTRACT**

An accelerometer is provided having a power circuit, a detection circuit, and a compensation circuit. The compensation circuit is operative to measure an offset voltage occurring between an output reference voltage from the power circuit and an output voltage from the detection circuit state, store the offset voltage during a zero acceleration, and output the stored offset voltage to alter the output voltage of the detection circuit.

**16 Claims, 3 Drawing Sheets**



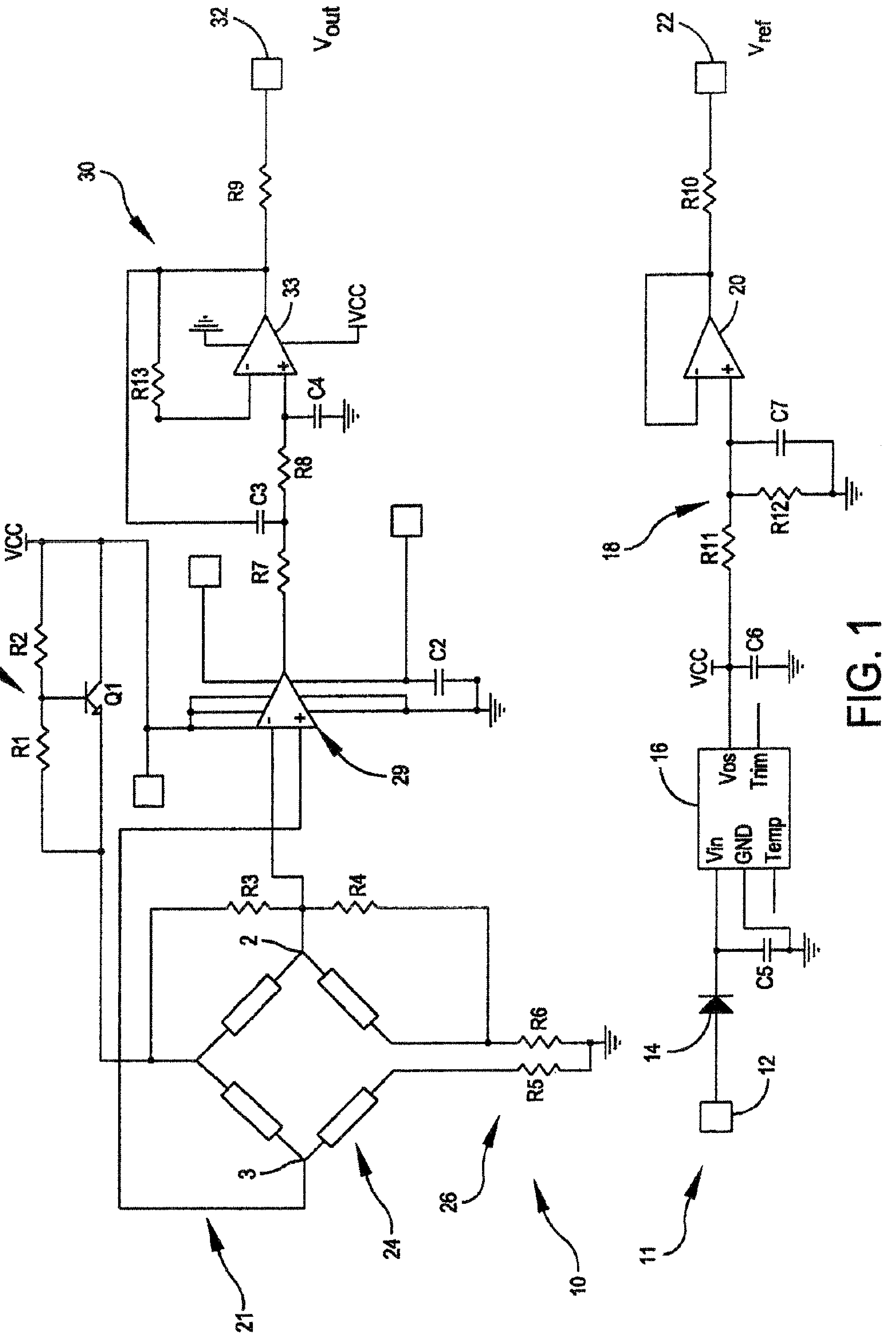

32
$V_{out}$
30
R9
33
VCC
R13
C4
C3
R8
R7
C2
29
28
R2
VCC
R1
Q1
R3
R4
2
3
R6
R5
21
24
26
10
22
$V_{ref}$
R10
20
C7
R12
18
R11
VCC
C6
16
Vos
Trim
Vin
GND
Temp
C5
14
12
11

FIG. 1

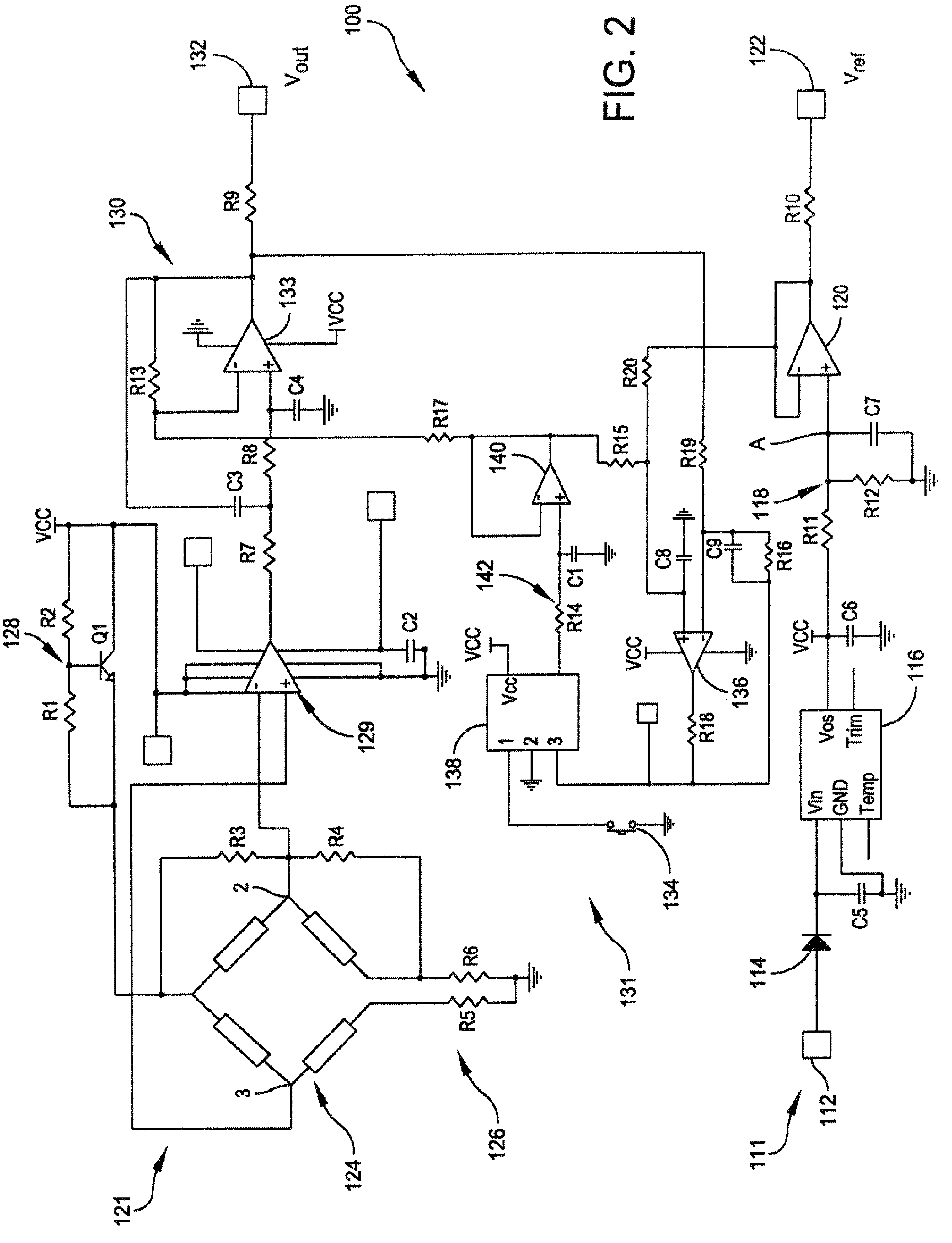

100
132
$V_{out}$
R9
130
133
VCC
R13
C4
R17
R8
C3
R7
VCC
R2
Q1
128
R1
129
C2
140
R15
R20
R19
C1
142
R14
VCC
Vcc
1
2
3
138
C8
C9
R16
VCC
136
R18
134
122
$V_{ref}$
R10
120
C7
A
118
R12
R11
VCC
C6
116
Vin
GND
Temp
Vos
Trim
C5
114
112
111
R3
R4
2
R6
R5
3
124
126
121
131

FIG. 2

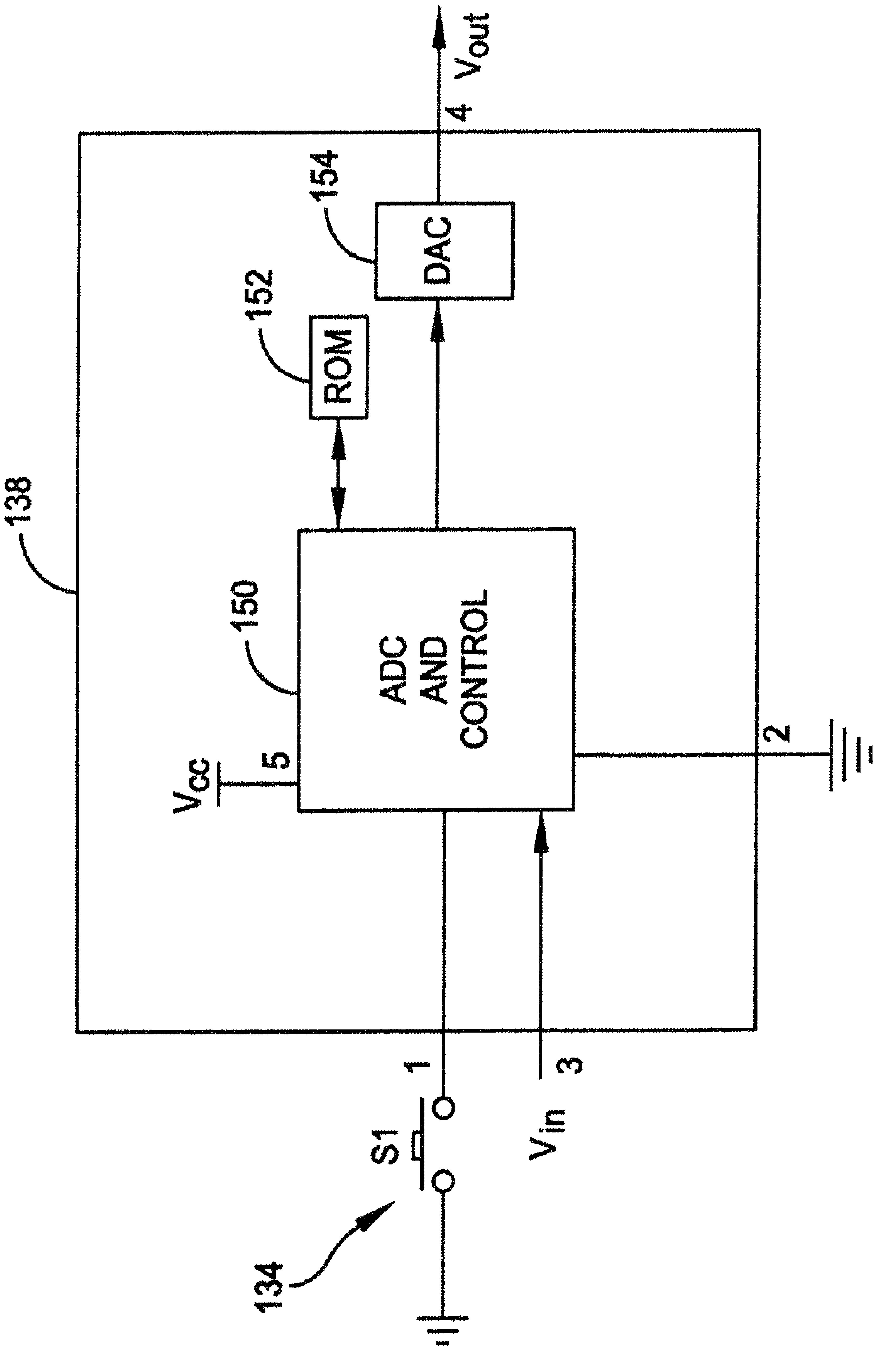

138
150
ADC
AND
CONTROL
152
ROM
154
DAC
4
$V_{out}$
$V_{cc}$
5
2
1
3
S1
$V_{in}$
134

FIG. 3

# DC RESPONSIVE TRANSDUCER WITH ON-BOARD USER ACTUATED AUTO-ZERO

## FIELD OF THE INVENTION

The present invention relates generally to transducers, and more particularly to accelerometers having circuitry compensating for drift.

## BACKGROUND

Electronic devices commonly utilize piezoelectric, piezoresistive and capacitive components to measure dynamic changes in mechanical variables such as acceleration, vibration, and mechanical shock. Such measurements are obtained by converting mechanical motion into an electrical signal. These devices are useful for a wide variety of applications including, but not limited to engineering, machine monitoring, biological study, navigation, medical applications, transportation, motion input, orientation sensing, and image stabilization.

One such class of electronic device is the accelerometer, which is capable of measuring acceleration by generating or altering a voltage proportional to a physical accelerative force acting thereon. Piezoelectric accelerometers are operative to convert mechanical force, such as a force applied to a piezoelectric crystal by a seismic mass, to an electrical signal. Piezo-resistive accelerometers use a piezo-resistive sensor element in place of the piezoelectric crystal. When a force acts upon a seismic mass, the stress induced on the piezoresistive gages causes a change in resistance, thereby altering a voltage provided across the gages of the sensor element. Unlike piezoelectric accelerometers, piezo-resistive accelerometers measure acceleration levels down to zero Hertz (i.e. static conditions).

While these devices are capable of producing accurate measurements when properly calibrated, their baseline voltage outputs (at zero acceleration for example) are subject to drift. Drift may be the result of temperature and/or environmental changes, component break-in, as well as packaging stresses that tend to relax over time. The output bias of a typical accelerometer output may shift, for example, a couple percent of full range as a result of its drift, thereby reducing the measurement accuracy of the device over its lifecycle.

In order to compensate for these errors, manufacturers often employ thermal conditioning techniques in an attempt to work out these anomalies prior to final device calibration. Such techniques include extended burn-in periods and thermal cycling of the devices. However, these techniques do not fully cure the problem. Accordingly, end users either have to allot for these measurement uncertainties or employ separate instrumentation, such as auto-zero signal conditioners, to periodically perform zero correction.

Additional solutions include the implementation of mechanical potentiometers integrated into the circuits of the devices for manually dialing-out this drift. However, potentiometer-based solutions tend to be time consuming and are of limited accuracy. Other devices employ auto-zero algorithms based on ADC-MCU-DAC arrangements (where ADC is analog to digital converter, DAC is digital to analog converter, and MCU is microcontroller unit) which induce digital noise and increase cost.

Accordingly, improved systems and methods of offset voltage correction are desired.

## SUMMARY

In one embodiment of the present invention a transducer-based device, such as a piezo-resistive accelerometer, is provided. The accelerometer comprises a power circuit for providing a reference voltage, and a detection circuit for generating an output voltage proportional to an accelerative force applied to the device. A compensation circuit is operatively connected to both the detection circuit and the power circuit for adjusting the zero-acceleration output voltage to match to the reference voltage.

In another embodiment of the present invention, a method of correcting an offset voltage of a transducer-based device is provided. The method comprises the steps of generating a fixed reference voltage, generating an output voltage proportional to an accelerative force applied to the device, measuring the offset voltage between the reference voltage and the output voltage in a zero-acceleration state, storing this offset voltage, and trimming the output voltage with the stored offset voltage in order to achieve a zero-offset voltage between the reference voltage and the output voltage.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a circuit diagram of a uncorrected piezo-resistive accelerometer.

FIG. **2** is a circuit diagram of a piezo-resistive accelerometer having an auto-compensation circuit according to an embodiment of the present invention.

FIG. **3** is a block diagram of an exemplary voltage reference module used in embodiments of the auto-compensation circuit of the present invention.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clear understanding of the present invention, while eliminating, for purposes of clarity, many other elements found in typical transducer-based sensors. However, because such elements are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements is not provided herein. The disclosure herein is directed to all such variations and modifications known to those skilled in the art.

In the following detailed description, reference is made to the accompanying drawings that show, by way of illustration, specific embodiments in which the invention may be practiced. It is to be understood that the various embodiments of the invention, although different, are not necessarily mutually exclusive. Furthermore, a particular feature, structure, or characteristic described herein in connection with one embodiment may be implemented within other embodiments without departing from the scope of the invention. In addition, it is to be understood that the location or arrangement of individual elements within each disclosed embodiment may be modified without departing from the scope of the invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, appropriately interpreted, along with the full range of equivalents to which the claims are entitled. In the drawings, like numerals refer to the same or similar functionality throughout several views.

Referring generally to FIG. **1**, the operation of an exemplary accelerometer **10** which may be used with embodiments of the present invention is described herein. The accelerometer **10** comprises a power circuit **11** configured to provide a constant reference voltage $V_{ref}$ at a first output terminal **22** of the accelerometer. A detection circuit **21** is operative to output a voltage corresponding to an applied accelerative force at a second output terminal **32** of the accelerometer. The exemplary accelerometer **10** is a differential measurement device, meaning the difference between these voltages is indicative of (e.g. proportional to) the measured acceleration. At zero acceleration, the output voltage from the power circuit **11** and the detecting circuit **21** should be equal, and voltage difference between the first and second terminals **22** and **32** zero volts (0V).

Still referring to FIG. **1**, the exemplary power circuit **11** comprises an input terminal **12** wherein an unregulated DC input voltage is supplied to the circuit **11**. A diode **14** may be arranged between the input terminal **12** and the voltage regulator **16** and configured to provide reverse polarity protection. The input voltage is provided to a voltage regulator **16** operative to output a constant voltage supply (for example 5V) to the downstream components of the power circuit **11** as well as to the detection circuit **21**. A voltage divider **18** comprised of resistors R**11** and R**12** is coupled to the output of the voltage regulator **16** to bring the output voltage at node A down to a pre-determined reference level $V_{ref}$ (e.g. 2.5V). This reference voltage $V_{ref}$ at node A is applied to the non-inverting terminal of buffering amplifier **20**. This ensures a constant reference voltage (e.g. 2.5V) is supplied to the first output terminal **22**.

The detection circuit **21** is operative to generate an output voltage $V_{out}$ indicative of an accelerative force acting on the accelerometer **10**. The detection circuit **21** generally comprises a supply voltage $V_{cc}$ provided by, in the exemplary embodiment, the 5V output of the voltage regulator **16** of the power circuit **11**. This supply voltage may be fed through a thermal correction circuit **28** including transistor Q**1** and resistors R**1** and R**2**. The thermal correction circuit is configured to adjust the voltage supplied therethrough to compensate for any device sensitivity to temperature change.

The temperature-corrected supply voltage powers a piezo-resistive transducer arrangement. As described above, piezo-resistive accelerometers utilize a piezo-resistive sensor element in place of a traditional piezoelectric crystal. Changes in the resistance of the gages due to forces exerted thereon are reflected in a voltage provided through the sensor element. In the exemplary embodiment, the piezo-resistive arrangement comprises a Wheatstone bridge **24** having four piezo-resistive elements, two increasing in resistance as accelerative force is applied to the accelerometer **10**, and two decreasing in resistance. Thus, the voltage outputs on either side of the bridge **24** move in opposite directions in response to a given acceleration. Gross correction for zero error may be provided by a resistor arrangement **26** comprising resistors R**5** and R**6**.

Each side labeled as nodes **2**,**3** of the bridge **24** is connected to the one of the inverting and non-inverting terminals of an instrumentation amplifier **29**. The amplifier **29** is operative to increase the gain of the output of the bridge **24**. In the exemplary embodiment, the amplifier **29** may feature a programmable gain for improved accuracy, control and calibration ability. The output of the amplifier **29** is supplied to, for example, a filtering arrangement, such a two pole Butterworth filter **30** comprising capacitors C**3** and C**4**, resistors R**7**, R**8** and R**13**, and amplifier **33**, for conditioning the output voltage supplied to the second output terminal **32**.

As described above, under zero acceleration conditions, the ideal voltage provided to the second output terminal **32** by the detection circuit **21** should be $V_{out}$=2.5V. Likewise, the reference voltage $V_{ref}$ provided at the first output terminal **22** should be $V_{ref}$=2.5V. Thus, the difference between the voltage at second output terminal **32** and the first output terminal **22** is zero, indicating zero acceleration. As an accelerative force acts on the accelerometer **10**, and the resistance of the piezo-resistive bridge arms is altered, the voltage output of respective nodes **2**,**3** of the bridge **24** are raised or lowered according to the direction of the acceleration. In turn, the output voltage provided to the second output terminal **32** is altered, creating a measurable difference with respect to that of the reference voltage $V_{ref}$ provided to the first output terminal **22**. This difference is proportional to the accelerative force on the accelerometer **10**.

As described above, voltage drift often occurs in the detection circuit **21** as the result of, for example, long-term thermal effects on the internal resistance of the circuit. Due to these variations, the output voltage provided to the second output terminal **32**, at zero acceleration for example, may be above or below the 2.5V target reference level. This offset voltage also affects the voltage difference between the output terminals **22**,**32** during acceleration events, thereby reducing the accuracy of the device.

In one embodiment of the present invention, drift correction is achieved by embedding a correction or compensation circuit between the power circuit **11** and the detecting circuit **21** of FIG. **1**. This arrangement is shown generally in FIG. **2**. An accelerometer **100** comprises a similar layout and function to that described above with respect to FIG. **1**. Specifically, the power circuit **111** comprises an input terminal **112** for supplying power through a diode **114** to a voltage regulator **116**. The output of the voltage regulator **116** may be provided to a voltage divider **118**, operative to supply a buffering amplifier **120** and, in turn, a first output terminal **122** with a constant reference voltage $V_{ref}$, of, for example, 2.5V. The output of the voltage regulator **116** is also supplied to components of the compensation circuit **131**, as well as the detection circuit **121**.

Similarly, the detection circuit **121** of the accelerometer **100** operates largely the same as described above with respect to FIG. **1**. The detection circuit **121** comprises a piezo-resistive arrangement in the form of a Wheatstone bridge **124** for providing a variable output voltage proportional to an accelerative force acting on the accelerometer **100**. An amplifier **129** increases the gain of the output of the bridge **124**, which is subsequently filtered through a Butterworth filter **130**, including an amplifier **133**, and provided to a second output terminal **132**. As described in detail above, the voltage difference between the first output terminal **122** and the second output terminal **132** is proportional to the measured acceleration of the accelerometer **100**.

Drift correction is provided by compensation circuit **131**. The compensation circuit **131** is operative to alter the voltage supplied to the inverting terminal of amplifier **133** in order to compensate for voltage drift within the detection circuit **121**. This compensation circuit **131** operates as follows.

The reference voltage $V_{ref}$ produced by the power circuit **111** is supplied to the non-inverting terminal of an operational amplifier **136** of compensation circuit **131**. Likewise, the inverting terminal of amplifier **136** is connected to the output of amplifier **133** of the detection circuit **121**. Accordingly, the output of amplifier **136** is equal to the difference between the reference voltage (2.5V) and the output of the detection circuit **121**. Thus, amplifier **136** provides analog bias calculation function. For example, under ideal conditions at zero-acceleration, the reference voltage and the voltage output from amplifier **133** will be equal (2.5V), and amplifier **136** will output no bias voltage. However, any voltage offset (drift) within the detection circuit **121** will be reflected by a higher or lower voltage output provided from amplifier **133** to the inverting terminal of amplifier **136**.

The output of amplifier **136** is equal to the offset voltage of the detection circuit **121**. Referring to FIGS. **2** and **3**, this offset voltage is fed as an input voltage $V_{in}$ is fed to input pin **3** of a voltage reference module **138**. The reference module **138** is operative to retain this offset voltage value. Specifically, an ADC/control model **150** is configured to store the offset voltage in memory **152**, for example, ROM or EEPROM, when pin **1** of the module **138** is brought low (e.g. to ground) via a switch **134**. In this way, when a user depresses the switch **134**, the offset voltage supplied to pin **3** is stored and retained in memory **152**. Once set, this offset voltage value is continually output through a DAC **154**, and output to pin **4** of the module **138** until the switch **134** is depressed again, and a new value is stored.

The offset voltage continually supplied from pin **4** may be connected to a voltage delayer **142** comprising resistor R**14** and capacitor C**1** for delaying the offset voltage in order to avoid errors produced during the analog bias calculation. The delayed offset voltage is then supplied to the non-inverting terminal of amplifier **140**. Amplifier **140** outputs a correction signal equal to the offset voltage to the inverting terminal of amplifier **133**. The correction signal trims the output voltage supplied to the second output terminal **132** to correct for the drift.

As indicated above, the voltage reference module **138** holds the offset voltage value upon depression of the switch **134** by a user. In this way, output voltage trimming according to the stored offset value will continue indefinitely, regardless of the measured acceleration of the accelerometer **100**. The offset voltage will be trimmed off or, or added to, the output voltage of the detection circuit **121** throughout its operating range. A new offset voltage is only set by a means of a subsequent control signal applied to the compensation circuit, such as through the activation of the switch **134**.

The embedded arrangement depicted herein provides for quick and easy transducer offset voltage correction, without the need for additional equipment, inaccurate and time-consuming manual calibration, or the high costs associated with additional equipment and operations.

While the foregoing describes embodiments of the present invention which utilize a control signal supplied to the compensation circuit by, for example, the activation of a switch, it is further envisioned other embodiments may implement alternative arrangements to set and store the offset voltage. For example, an automatic controller may be configured in place of, or in parallel with the switch arrangement described above. This controller is adapted to provide a control signal for setting and storing the offset voltage by the compensation circuit. The control signal may be output from an evaluation circuit that compares the output of the first and second output terminals over time in order to make a determination that the device is at rest (i.e. zero acceleration). For example, the evaluation circuit may compare the voltage output at the first and second output terminals for an application-specific, predetermined time period. If the voltage difference remains constant between the first and second output terminals over the predetermined time period (indicative of the device under zero acceleration), the controller may output the control signal to the compensation circuit for setting and storing the offset voltage.

While the foregoing describes embodiments of the present invention used with an exemplary piezo-resistive accelerometer, it is envisioned that additional embodiments of the present invention may be implemented into numerous other types of transducer-based devices, including piezoelectric or strain-gauge based accelerometers without departing from the scope of the present invention.

While the foregoing describes exemplary embodiments and implementations, it will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention.

What is claimed is:

**1**. A transducer-based measuring device comprising:

a power circuit for providing a reference voltage to a first output terminal of the measuring device;

a detection circuit for providing an output voltage to a second output terminal of the measuring device, the output voltage indicative of an accelerative force acting on the measuring device; and

a compensation circuit embedded between the power circuit and the detection circuit of the measuring device and operatively connected to both the power circuit and the detection circuit, the compensation circuit configured to measure and store an offset voltage between the reference voltage and the output voltage, and continuously output the stored offset voltage to the detection circuit to provide an adjusted output voltage representative of a zero-offset condition.

**2**. The device of claim **1**, wherein the compensation circuit further comprises a voltage reference module operative to store and continuously output the offset voltage.

**3**. The device of claim **2**, wherein the voltage reference module stores the offset voltage upon receipt of a control signal, and wherein the offset voltage output by the voltage reference module remains constant after receipt of the control signal and until receipt of a subsequent control signal.

**4**. The device of claim **3**, wherein the control signal is generated by a user-activated switch arranged on the device.

**5**. The device of claim **3**, further comprising a processor operative to generate the control signal upon a determination that the device is in a zero acceleration state.

**6**. The device of claim **1**, wherein the compensation circuit further comprises an operational amplifier coupled to the output voltage and the reference voltage, the amplifier configured to output the offset voltage measured between the reference voltage and the output voltage.

**7**. The device of claim **6**, wherein the detection circuit comprises a second operational amplifier responsive to the output voltage of the detection circuit and the offset voltage and configured to alter the output voltage supplied to the second output terminal.

**8**. The device of claim **1**, wherein the detection circuit comprises at least one of a piezo-resistive, piezoelectric, or strain gauge element configured to alter the output voltage of the detection circuit indicative of an accelerative force acting on the measuring device.

**9**. The device of claim **8**, wherein the detection circuit comprises a plurality of piezo-resistive elements arranged in a Wheatstone bridge.

**10**. A method of correcting an offset voltage of a transducer-based measuring device, the method comprising:

generating a reference voltage;

generating an output voltage indicative of an accelerative force applied to the measuring device;

measuring an offset voltage between the reference voltage and the output voltage with a compensation circuit embedded within the measuring device, and

adjusting the output voltage with the measured offset voltage in order to achieve a zero-offset voltage between the reference voltage and the output voltage in a zero acceleration state.

**11**. The method of claim **10**, further comprising the step of storing the measured offset voltage in response to a control signal.

**12**. The method of claim **11**, wherein the control signal is generated while the device is in a zero acceleration state.

**13**. The method of claim **11**, further comprising the step of continuously outputting the stored offset voltage to adjust the output voltage.

**14**. The method of claim **11**, wherein the control signal is generated in response to the user-activation of a switch arranged on the measuring device.

**15**. The method of claim **11**, wherein the control signal is automatically generated by a processor.

**16**. A transducer-based measuring device comprising:

a power circuit configured to generate a reference voltage;

a detection circuit configured to generate an output voltage indicative of an accelerative force applied to the measuring device; and

a compensation circuit embedded within the measuring device and configured to:

measure an offset voltage between the reference voltage and the output voltage; and

adjust the output voltage with the measured offset voltage in order to achieve a zero-offset voltage between the reference voltage and the output voltage in a zero acceleration state.

* * * * *